Gait variability and symmetry remain consistent during high-intensity 10000 m treadmill running

Original article

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Abstract

The aim of this study was to analyze changes in gait variability and symmetry in distance runners. Fourteen competitive athletes ran on an instrumented treadmill for 10000 m at speeds equivalent to 103% of their season's best time. Spatiotemporal and ground reaction force data were recorded at 1500, 3000, 5000, 7500 and 9500 m. Gait variability and inter-leg symmetry were measured using median absolute deviation (MAD) and the symmetry angle, respectively. There were no overall changes during the running bout for absolute values, symmetry angles or variability, and there were only moderate changes in variability between successive testing distances for three variables. Even with these few changes, variability was low (< 4%) at all distances for all variables measured and, on average, the athletes were symmetrical for five of the seven gait variables measured. There were greater mean asymmetry values for flight time (1.1 – 1.4%) and for impact force (2.0 – 2.9%), which might have occurred because of muscle latency as the lower limb responded passively to impact during initial contact. Although most athletes were asymmetrical (> 1.2%) for at least one variable, no one was asymmetrical for more than four of the seven variables measured. Being asymmetrical in a few variables is therefore not abnormal and not indicative of asymmetrical gait and given many practitioners analyze symmetry (and variability) on an individual, case-study basis, caution should be taken when assessing the need for corrective interventions.

Keywords: athletics, endurance, fatigue, imbalance, spatiotemporal variables

1. Introduction

Movement variability is a normal and functional feature of human movement prevalent in sports performance. Too much or too little variability within movement can be detrimental in performing motor tasks (Davids et al., 2003; Srinivasan et al., 2015). It has been identified that expert performers exhibit reduced variability in outcome-related variables compared with lesser-skilled performers (Fleisig et al., 2009), and that the principal variables that determine running speed (i.e., step length and frequency) have reduced variability in expert runners (Nakayama et al., 2010), which is another example of reduced outcome variability. Beyond sports performance, there is evidence of increased variability in pathological gait compared with healthy gait (e.g., outcome measures such as step length and frequency), such as in Parkinson’s disease (Moon et al., 2016), and high gait variability has been associated with increased fall risk in the elderly (Toebes et al., 2012). Conversely, it has been suggested that increased movement variability between strides in running (e.g., variability of coordination between segments) is beneficial as it allows for an even distribution of stresses across the tissues and the ability to adapt to any changes that arise in the environment (Hamill et al., 1999). There might therefore be a window of optimal variability that exists depending on the motor task (Meardon et al., 2011) within which an individual will vary movement to achieve the desired outcome, and which alters depending on internal and external factors.

One factor that might affect movement variability is how fatigued the individual is at any given time during the task. In general, variability is expected to increase with prolonged activity or muscle fatigue (Meardon et al., 2011; Missenard et al., 2008). This might be because movement variability allows flexibility in adjusting to perturbations in the environment and thus helps to preserve performance, as was found to occur with muscle fatigue in occupational tasks such as hammering (Srinivasan and Mathiassen, 2012).

However, the relationship between movement variability and movement outcome, and its change in response to increased fatigue, has not been fully investigated in sports performance. Previous studies have examined changes in movement variability before, after or at a specific time during the fatiguing protocol (e.g., Nakayama et al., 2010), yet few have measured whether it changes at multiple points during a fatiguing protocol within a well-trained cohort of sportspeople. Understanding the consistency of variability is thus important in understanding whether it changes as fatigue increases and, for researchers, in terms of making an informed choice as to when to sample for an athlete's typical variability during exercise.

Whereas movement variability can measure, for example, the similarity of movements within a limb, between-limb similarities are typically measured using symmetry scores. Although having a dominant limb is normal, it can be disadvantageous to have asymmetrical lower limbs in activities such as running, as one limb can be required to increase work to compensate for the weaker side (Levine et al., 2012). Asymmetry occurs when there is any deviation from symmetry, i.e., the exact replication of one limb's movement by the other (Exell et al., 2012). Measurements of asymmetry have been used in running research to highlight not only an increase in injury risk (Schache et al., 2009), but also by physicians to quantify functional deficits resulting from lower limb injury (Girard et al., 2017). However, being asymmetrical for any given spatiotemporal variable (e.g., step length) does not signify that the individual has an inter-limb imbalance that negatively affects gait, as the same outcome is achievable in different ways (Levine et al., 2012); it is therefore important to also consider the causative factors, such as external forces (Sadeghi et al., 2000). It would be rare for both lower limbs to replicate each other's movements exactly, as variability within a limb means that it does not even replicate its own movements precisely. Even in healthy individuals, it has been suggested that the underlying musculoskeletal structure can be asymmetrical, e.g., the Achilles tendon (Bohm et al., 2015). Criteria for meaningful differences between limbs depend on the measure used; for example, previous research on racewalking found that a symmetry angle of 1.2% or more, established using difference testing and effect sizes on multiple (> 40) right and left steps, was indicative of an individual being asymmetrical for that variable (Tucker and Hanley, 2017), and could be a practically useful reference for other gait studies. The symmetry angle (Zifchock et al., 2008) is a dimensionless measure of asymmetry that does not suffer from artificial inflation, unlike the symmetry index that requires a reference value (Exell et al., 2012), and is therefore a robust measure of asymmetry that can be used across spatiotemporal and kinetic variables.

Like variability, it is possible that symmetry values alter during an exercise bout, for example when the athlete is fatigued, or as they become accustomed to its intensity. Recent research by Radzak et al. (2017) found differences in symmetry angle between rested and fatigued-state running for several gait variables, although other variables were asymmetrical both before and after the fatiguing protocol. Similar research (Brown et al., 2014; Girard et al., 2017) found that dominant and non-dominant legs fatigued at similar rates, and thus inter-leg asymmetries are not likely due to lower limb dominance (Brown et al., 2014). The measurement of variability or symmetry at a single instant might not represent an athlete's typical state, given that intensive endurance activity usually results in local muscular fatigue (Mizrahi et al., 2000). Furthermore, it is important to assess asymmetry on an individual basis as athletes employ different mechanisms for contralateral limbs to achieve similar outcomes (Exell et al., 2017). Previous research has predominantly analyzed variability and symmetry changes before and after fatiguing exercise (e.g., Gates and Dingwell, 2011), but it will be useful to identify any changes that occur at different times during the exercise bout. The measurement of gait variables at multiple distances will allow for an appreciation of how frequently an athlete experiences variability or asymmetry, and provide an indication of the validity of a single measurement in assessing these factors. The aim of this study was to analyze changes in variability and symmetry during 10000 m treadmill running. Based on previous research on changes in variability and symmetry with fatigue, it was hypothesized that both would increase during a high-intensity continuous running protocol.

2. Methods

2.1. Participants

The study was approved by the Faculty Research Ethics Committee, and 14 competitive male distance runners (31 ± 7 yrs, 1.79 ± 0.07 m, 66.4 ± 5.6 kg) gave written informed consent. Their season's best time for 10 km (in road racing) ranged from 31:00 to 35:20. All participants were over the age of 18 and free from injury.

2.2. Protocol

After a 10-min warm-up and familiarization period (Matsas et al., 2000), each participant ran for 10000 m on an instrumented Gaitway treadmill (h/p/Cosmos, Traunstein, Germany) (LaRoche et al., 2012) at a speed equivalent to 103% of their season's best 10 km road race speed (Hanley, 2015). Each athlete ran at a constant pace for the duration of the test, with a mean belt speed of 17.56 $km \cdot h^{-1}$ (± 0.59). The treadmill's inclination was set at 0% during data collection (Paquette et al., 2017). Participants were all habitual treadmill users and wore their normal training clothing and footwear for indoor training sessions. The treadmill incorporated two in-dwelling piezoelectric force plates (Kistler, Winterthur, Switzerland) that recorded vertical ground reaction forces (GRF) (1000 Hz) and temporal data. The force plates also recorded the position of the center of pressure from which step length was measured.

Data were collected for 30 s at 1500, 3000, 5000, 7500 and 9500 m, which allowed for the collection of 45 (± 3) steps per foot during each sampling period. The Rate of Perceived Exertion (RPE) Scale (Borg, 1975) was used to measure perception of fatigue on a scale of 6 – 20 (e.g., a score of 11 represented a 'fairly light' rating, and 15 represented a 'hard' rating).

2.3. Data processing

The GRF data were exported and smoothed using a recursive second-order, low-pass Butterworth filter (zero phase-lag). The optimal cut-off frequency was calculated during a pilot test using residual analysis (Winter, 2005). The results showed an optimal cut-off frequency ranging from 48 – 52 Hz, so it was decided to use 50 Hz as the cut-off frequency for all trials. The mean and standard deviation (SD) of the noise occurring during the final 50 ms before ground contact (visual inspection) were calculated, and initial contact was considered to begin when the vertical force magnitude was greater than the mean plus 3SD of the noise. The mean and 3SD of the noise during the first 50 ms after toe-off were used in a similar way to identify the end of contact and the beginning of flight. The vertical GRF data variables analyzed were impact peak force, maximum force and impulse. The impact peak was defined as the highest recorded force during the first 70 ms of contact, and the maximum force was identified as the next peak in the vertical GRF trace during midstance (and whose magnitude was always greater than the impact peak force) (Figure 1) (Hanley, 2015; Watkins, 2010). Impulse was also calculated in the vertical direction only as the time integral of the force curve using the trapezoidal rule (Caderby et al., 2013). All kinetic variables were normalized for each athlete's body weight (BW). Step length was defined as the distance from each foot strike to the next foot strike of the opposite foot. Contact time was defined as the time duration from initial contact to toe-off, whereas flight time was the time duration from toe-off of one foot to initial contact of the other foot (Padulo et al., 2014). Step frequency was calculated as the reciprocal of step time (itself calculated as the sum of contact time and flight time).

**** Figure 1 near here ****

2.4. Analysis

Gait variability was calculated using median absolute deviation (MAD) (Leys et al., 2013) where the MAD was calculated for the left and right legs separately and then the mean calculated for each participant. The mean MAD scores were calculated as percentages of the original median value to compare between groups and variables. Separately, the MAD scores were also multiplied by the constant scale factor of 1.4826 (Leys et al., 2013), and the median plus or minus 2.5 times the result of this calculation used for outlier detection (Leys et al., 2013). Outliers were removed before the calculation of means and standard deviations (absolute values) and symmetry values to reduce the chances of false positives (Leys et al., 2013); overall, 4.6% of the recorded values were removed.

For each participant, inter-leg symmetry was measured using the symmetry angle and rectified so that all values were positive (Exell et al., 2012). The symmetry angle was calculated using the equation below (Zifchock et al., 2008):

$$\text{Symmetry angle} = [(45° – \arctan(X_{\text{left}} / X_{\text{right}}) / 90°)] \text{ X } 100\%$$

where X was the mean value for a variable on each leg.

To measure any changes in variability or symmetry within the athletes as they completed the treadmill run, one-way repeated measures analysis of variance (ANOVA) was conducted with repeated contrast tests conducted to identify changes between successive measurements (Field, 2009). An alpha level of 5% was set for all statistical tests. Effect sizes (ES) for differences between successive measurements were calculated using Cohen's *d* (Cohen, 1988) and considered to be either trivial (ES: < 0.20), small (0.21 – 0.60), moderate (0.61 – 1.20), large (1.21 – 2.00), or very large (2.01 – 4.00) (Hopkins et al., 2009); the effect size was also reported using partial eta-squared (η_p^2). On those occasions where Cohen's *d* was calculated, only those instances where the effect sizes were moderate or larger have been indicated. Individual participants' inter-leg differences were considered asymmetrical if the symmetry angle value was greater than 1.2% (Tucker and Hanley, 2017) and Cohen's *d* was ≥ 1.21. Athletes were considered to be asymmetrical for any particular variable if more than half of their symmetry angles were above 1.2% (with corresponding large effect sizes) (i.e., asymmetrical at three or more of the five distances) and their mean symmetry angle was above 1.2% (averaged across all five distances).

3. Results

The mean absolute values for each of the variables analyzed are shown in Table 1; there were no differences found for any variable. The results for gait variability (MAD scores) are shown in Table 2, whereas the results for symmetry angles are shown in Table 3. There were no overall effects for distance, although variability in maximum force decreased between 1500 and 3000 m ($p = 0.005$, ES = 1.08, $\eta_p^2 = .470$), whereas variability in impulse increased between 5000 and 7500 m ($p = 0.017$, ES = 0.74, $\eta_p^2 = .363$). Similarly, variability in impact force increased between 7500 and 9500 m ($p = 0.008$, ES = 0.62, $\eta_p^2 = .428$). There were no changes in mean symmetry for any variable with distance run. Eleven of the athletes were heel-strikers whereas the other three were midfoot-strikers; distinct impact peaks were visible for all athletes. The mean RPE score was 11 (± 1), 12 (± 1), 15 (± 2), 16 (± 2) and 18 (± 3) at the five successive measurement distances.

**** Table 1 near here ****

**** Table 2 near here ****

**** Table 3 near here ****

The number and percentage of athletes who were considered asymmetrical for any particular variable at each distance are shown in Table 4. All athletes were considered symmetrical for at least one variable at all five measurement distances, although only two were symmetrical for all variables. Table 5 shows the mean scores for symmetry angles across all five distances for each individual runner.

**** Table 4 near here ****

**** Table 5 near here ****

4. Discussion

The aim of this study was to analyze changes in variability and symmetry during 10000 m treadmill running. Mean variability was low (< 4%) for all gait variables measured at all distances, and only moderate changes occurred between a small number of successive measurements for some variables, which were still found to be below 4%. It was found previously that in maximum voluntary isometric contraction tasks there was an increase in force variability with fatigue with a decrease in mean force output (Missenard et al., 2008), but this was not replicated in this novel study where athletes completed high-intensity but sub-maximal cyclic running movements. Movement consistency is crucial in gait because it determines one's ability to perform intentional variations of the stride (Danion et al., 2003), and the low variability found here is indicative of that consistency. The movement variability for GRF variables was greater than for spatiotemporal variables, possibly because positive functions of movement variability include facilitating changes in coordination, adapting to environmental changes, and preventing the same tissues being loaded each time (Bartlett et al., 2007). There were also no changes in mean symmetry with distance run, similar to previous research on elite-standard racewalkers (Tucker and Hanley, 2017); as there were no changes in absolute mean values either, ultimately there were very few effects of fatigue in these well-trained distance runners and so we rejected our hypothesis. During fatigue, it is possible that an individual's motor strategies are re-organized so that performance is preserved (Sparto et al., 1997) and, in running, this was achieved in a way that maintained the key kinetic and spatiotemporal variables.

Mean asymmetry values were low for five of the seven measured variables, with scores lower than the symmetry angle criterion value of 1.2% at all five distances, highlighting that there were few differences between limbs (as well as within them) that might have resulted from long-term, high-quality training in these runners. However, mean symmetry angles above 1.2% were found for impact force at four of the five distances, and for flight time at 7500 and 9500 m, indicating that asymmetry was more common in these variables, and especially during the second half of the run. Whereas no more than 36% of athletes displayed asymmetry for flight time at any distance, the proportion of runners showing asymmetry for impact force ranged from 29 to 64%. This might have been because the leg muscles could not respond to the impact force because of muscle latency (Watkins, 2010), just as a function of movement variability might be to attenuate impact shocks (Bartlett et al., 2007), and in doing so the left and right legs accommodated impacts differently. By contrast, only one athlete was considered asymmetrical for step length, and one for step frequency. Together with contact time, these spatiotemporal variables showed least variability and asymmetry, demonstrating how these determinants of running speed are consistent between- and within-limbs throughout a fatiguing exercise bout, despite (or because of) differences in underlying kinetic variables. It should be noted that asymmetry between GRF variables alone (e.g., if the researcher or clinician is solely reliant on force plates) could therefore provide an inconclusive diagnosis of left-right differences if the main outcome variables (i.e., step length and frequency) cannot be measured. Equally, even if step length and frequency are not asymmetrical, any large inter-limb differences should be investigated in case they are symptomatic of muscles on one side of the body compensating for the other (Levine et al., 2012).

In a clinical setting or in analyses of elite-standard sportspeople, it is not uncommon to evaluate gait on an individual basis rather than using group means (e.g., Salo et al., 2011), which is especially important with regard to asymmetry because of its individual nature (Exell et al., 2017). Athletes' symmetry angles were analyzed at five distances to decide whether asymmetry was consistently present in any individual athlete. A criterion was applied that athletes had to have more than half of their symmetry angles above 1.2% (and Cohen's $d \geq 1.21$) to be considered asymmetrical (in addition to having means above 1.2% / 1.21, respectively, across all five measurements) to prevent any single, outlying result from affecting this decision. The results showed that although asymmetry could be present for an athlete on some occasions (e.g., one athlete's contact time at 7500 and 9500 m), they should not always be considered asymmetrical for that variable if those results were the exception rather than the rule. Although it is not always feasible to perform multiple measurements, researchers and physicians should nonetheless be careful not to assume the presence of symmetry (or asymmetry) based on a single or limited number of measurements. In this study, approximately 5% of results were removed before analysis because they were found to be outliers, highlighting further the need to apply caution when analyzing a small sample. Additionally, although most athletes were asymmetrical for at least one variable, no one was asymmetrical for more than four of the seven variables measured. The finding that an athlete has asymmetry in at least a few variables is therefore not abnormal and not necessarily indicative of an imbalance that needs correcting, and an overall assessment of an individual's gait is necessary when deciding whether an intervention is advised.

In this study, using a treadmill to control environmental constraints was invaluable in ensuring a constant pace and running surface, which meant that those natural elements found in outdoor running, such as obstacles, turns and changes in gradient, were eliminated as factors that could cause changes in variability or symmetry. Because of this, it is expected that using a treadmill with a constant belt speed (task constraint) and level inclination produces inherently low movement variability compared with outdoor running (Jordan et al., 2006; Paquette et al., 2017) or laboratory-based overground walking (Hollman et al., 2016), and the athletes in this study would most likely have higher variability when running overground, outdoors or in variable weather. This is also true of asymmetry, where the constant belt speed was an external imposed constraint that might have imposed an artificial motor control of gait, and mitigated the natural asymmetry and variability that occurs in overground conditions (Harris-Love et al., 2001). In addition, a limitation of the Gaitway treadmill used was that shear forces could not be measured and thus it was not possible to measure, for example, variability in braking or propulsive (anteroposterior) forces, which could be important with regard to limb differences in contributing to maintenance of forward momentum. Additionally, because treadmill running is stationary with respect to the ground, the Gaitway system uses belt movement and COP measurements on each force plate to determine step length (LaRoche et al., 2012), which are more difficult to corroborate with video measurements than in overground gait. Gait measurements found using treadmills should therefore be treated with caution and, in particular, treadmills might not be suitable for measuring variability in certain populations such as the elderly and patients with degenerative neurological disorders (Dingwell et al., 2001). Treadmills should be limited to those populations who use them frequently (in sports training, for example); with such an appropriate test population, instrumented treadmills are nevertheless particularly well suited to analyzing gait as they prevent targeting of force plates and allow for a large number of samples to be collected in a short period (LaRoche et al., 2012). Research that is conducted on overground gait but during a long (> 30 min), high-intensity running bout can add to this new study on treadmill running, and potentially examine coordination variability changes with fatigue.

Conflict of interest statement

The authors have no conflicts of interest that are relevant to the content of the manuscript. No sources of funding were used to assist completion of the study or preparation of the manuscript.

References

Bartlett, R., Wheat, J., Robins, M., 2007. Is movement variability important for sports biomechanists? Sports Biomech. 6, 224-243. doi: 10.1080/14763140701322994

Bohm, S., Mersmann, F., Marzilger, R., Schroll, A., Arampatzis, A., 2015. Asymmetry of Achilles tendon mechanical and morphological properties between both legs. Scand. J. Med. Sci. Sports 25, e124-e132. doi: 10.1111/sms.12242

Borg, G., 1975. Simple rating methods for estimation of perceived exertion. In: Borg, G. (Ed.), Physical Effort and Work. Pergamon Press, New York, NY, pp. 39-46.

Brown, A.M., Zifchock, R.A., Hillstrom, H.J., 2014. The effects of limb dominance and fatigue on running biomechanics. Gait Posture 39, 915-919. doi: 10.1016/j.gaitpost.2013.12.007

Caderby, T., Yiou, E., Peyrot, N., Bonazzi, B., Dalleau, G., 2013. Detection of swing heel-off event in gait initiation using force-plate data. Gait Posture 37, 463-466. doi: 10.1016/j.gaitpost.2012.08.011

Cohen, J., 1988. Statistical power analysis for the behavioural sciences (2nd ed.). Lawrence Erlbaum, Hillsdale, NJ.

Danion, F., Varraine, E., Bonnard, M., Pailhous, J., 2003. Stride variability in human gait: the effect of stride frequency and stride length. Gait Posture 18, 69-77. doi: 10.1016/S0966-6362(03)00030-4

Davids, K., Glazier, P.S., Araujo, D., Bartlett, R., 2003. Movement systems as dynamical systems: the functional role of variability and its implication for sports medicine. Sports Med. 33, 245-260. doi.org/10.2165/00007256-200333040-00001

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R., Sternad, D., 2001. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J. Biomech. Eng. 123, 27-32. doi: 10.1115/1.1336798

Exell, T.A., Irwin, G., Gittoes, M.J.R., Kerwin, D.G., 2017. Strength and performance asymmetry during maximal velocity sprint running. Scand. J. Med. Sci. Sports 27, 1273-1282. doi: 10.1111/sms.12759

Exell, T.A., Irwin, G., Gittoes, M.J.R., Kerwin, D.G., 2012. Implications of intra-limb variability on asymmetry analyses. J. Sports Sci. 30, 403-409. doi: 10.1080/02640414.2011.647047

Field, A.P., 2009. Discovering statistics using SPSS (3rd ed.). Sage, London.

Fleisig, G., Chu, Y., Weber, A., Andrews, J., 2009. Variability in baseball pitching biomechanics among various levels of competition. Sports Biomech, 8, 10-21. doi: 10.1080/14763140802629958

Gates, D.H., Dingwell, J.B., 2011. The effects of muscle fatigue and movement height on movement stability and variability. Exp. Brain Res. 209, 525-536. doi: 10.1007/s00221-011-2580-8

Girard, O., Brocherie, F., Morin, J.-B., Millet, G.P., 2017. Lower limb mechanical asymmetry during repeated treadmill sprints. Hum. Mov. Sci. 52, 203-214. doi: 10.1016/j.humov.2017.02.008

Hamill, J., van Emmerik, R.E.A., Heiderscheit, B.C., Li, L., 1999. A dynamical systems approach to lower limb running injuries. Clin. Biomech., 14, 297-308. doi: 10.1016/S0268-0033(98)90092-4

Hanley, B., 2015. Gait alterations during constant pace treadmill racewalking. J. Strength Cond. Res. 29, 2142-2147. doi: 10.1519/JSC.0000000000000875

Harris-Love, M.L., Forrester, L.W., Macko, R.F., Silver, K.H.C., Smith, G.V., 2001. Hemiparetic gait parameters in overground versus treadmill walking. Neurorehabil. Neural Re. 15, 105-112. doi: 10.1177/154596830101500204

Hollman, J.H., Watkins, M.K., Imhoff, A.C., Braun, C.E., Akervik, K.A., Ness, D.K., 2016. A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions. Gait Posture 43, 204-209. doi: 10.1016/j.gaitpost.2015.09.024

Hopkins, W.G., Marshall, S.W., Batterham, A.M., Hanin, J., 2009. Progressive statistics for studies in sports medicine and exercise science. Med. Sci. Sports Exerc. 41, 3-12. doi: 10.1249/MSS.0b013e31818cb278

Jordan, K., Challis, J.H., Newell, K.M., 2006. Long range correlations in the stride interval of running. Gait Posutre 24, 120-125. doi: 10.1016/j.gaitpost.2005.08.003

LaRoche, D.P., Cook, S.B., Mackala, K., 2012. Strength asymmetry increases gait asymmetry and variability in older women. Med. Sci. Sports Exerc. 44, 2172-2181. doi: 10.1249/MSS.0b013e31825e1d31

Levine, D., Richards, J., Whittle, M.W., 2012. Whittle's gait analysis (5th ed.). Churchill Livingstone, Edinburgh.

Leys, C., Ley, C., Klein, O., Bernard, P., Licata, L., 2013. Detecting outliers: do not use standard deviation around the mean, use absolute deviation around the median. J. Exp. Soc. Psychol. 49, 764-766. doi: 10.1016/j.jesp.2013.03.013

Matsas, A., Taylor, N., McBurney, H., 2000. Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. Gait Posture 11, 46-53. Retrieved from http://www.sciencedirect.com/science/article/pii/S096663629900048X

Meardon, S.A., Hamill, J., Derrick, T.R., 2011. Running injury and stride time variability over a prolonged run. Gait Posture 33, 36-40. doi: 10.1016/j.gaitpost.2010.09.020

Missenard, O., Mottet, D., Perrey, S., 2008. Muscular fatigue increases signal-dependent noise during isometric force production. Neurosci. Lett. 437, 154-157. doi: 10.1016/j.neulet.2008.03.090

Mizrahi, J., Verbitsky, O., Isakov, E., 2000. Fatigue-related loading imbalance on the shank in running: a possible factor in stress fractures. Ann. Biomed. Eng. 28, 463-469. doi: 10.1114/1.284

Moon, Y., Sung, J., An, R., Hernandez, M.E., Sosnoff, J.J., 2016. Gait variability in people with neurological disorders: a systematic review and meta-analysis. Hum. Mov. Sci. 47, 197-208. doi: 10.1016/j.humov.2016.03.010

Nakayama, Y., Kudo, K., Ohtsuki, T., 2010. Variability and fluctuation in running gait cycle of trained runners and non-runners. Gait Posture 31, 331-335. doi: 10.1016/j.gaitpost.2009.12.003

Padulo, J., Chamari, K., Ardigò, L.P., 2014. Walking and running on treadmill: the standard criteria for kinematics studies. Muscles Ligaments Tendons J. 4, 159-162. doi: 10.11138/mltj/2014.4.2.159

Paquette, M.R., Milner, C.E., Melcher, D.A., 2017. Foot contact angle variability during a prolonged run with relation to injury history and habitual foot strike pattern. Scand. J. Med. Sci. Sports 27, 217-222. doi: 10.1111/sms.12647

Radzak, K.N., Putnam, A.M., Tamura, K., Hetzler, R.K., Stickley, C.D., 2017. Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. Gait Posture 51, 268-274. doi: 10.1016/j.gaitpost.2016.11.005

Sadeghi, H., Allard, P., Prince, F., Labelle, H., 2000. Symmetry and limb dominance in able-bodied gait: a review. Gait Posture 12, 34-45. doi: 10.1016/S0966-6362(00)00070-9

Salo, A.I.T., Bezodis, I.N., Batterham, A.M., Kerwin, D.G., 2011. Elite sprinting: are athletes individually step-frequency or step-length reliant? Med. Sci. Sports Exerc. 43, 1055-1062. doi: 10.1249/MSS.0b013e318201f6f8

Schache, A.G., Wrigley, T.V., Baker, R., Pandy, M.G., 2009. Biomechanical response to hamstring muscle strain injury. Gait Posture 29, 332-338. doi: 10.1016/j.gaitpost.2008.10.054

Sparto, P.J., Parnianpour, M., Reinsel, T.E., Simon, S., 1997. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. J. Orthop. Sports Phys. Ther. 25, 3-12. doi: 10.2519/jospt.1997.25.1.3

Srinivasan, D., Mathiassen, S.E., 2012. Motor variability in occupational health and performance. Clin. Biomech. 27, 979-993. doi: 10.1016/j.clinbiomech.2012.08.007

Srinivasan, D., Samani, A., Mathiassen, S.E., Madeleine, P., 2015. The size and structure of arm movement variability decreased with work pace in a standardised repetitive precision task. Clin. Biomech. 58, 128-139. doi: 10.1080/00140139.2014.957736

Toebes, M.J.P., Hoozemans, M.J.M., Furrer, R., Dekker, J., van Dieën, J.H., 2012. Local dynamic stability and variability of gait are associated with fall history in elderly subjects. Gait Posture 36, 527-531. doi: 10.1016/j.gaitpost.2012.05.016

Tucker, C.B., Hanley, B., 2017. Gait variability and symmetry in world-class junior and senior race walkers. J. Sports Sci. 35, 1739-1744. doi: 10.1080/02640414.2016.1235793

Watkins, J., 2010. Structure and function of the musculoskeletal system (2nd ed.). Human Kinetics, Champaign, IL.

Winter, D.A., 2005. Biomechanics and motor control of human movement (3rd ed.). John Wiley & Sons, Hoboken, NJ.

Zifchock, R.A., Davis, I., Higginson, J., Royer, T., 2008. The symmetry angle: a novel, robust method of quantifying asymmetry. Gait Posture 27, 622-627. doi: 10.1016/j.gaitpost.2007.08.006

Table 1. Mean (± SD) absolute values at each distance.

	1500 m	3000 m	5000 m	7500 m	9500 m
Step length (m)	1.61 ± 0.11	1.62 ± 0.11	1.63 ± 0.10	1.63 ± 0.10	1.63 ± 0.11
Step frequency (Hz)	3.04 ± 0.19	3.02 ± .19	3.00 ± .18	3.01 ± 0.19	3.01 ± 0.19
Contact time (s)	.194 ± .015	.193 ± .016	.193 ± .016	.191 ± .016	.189 ± .015
Flight time (s)	.136 ± .010	.139 ± .010	.142 ± .010	.143 ± .011	.144 ± .011
Impact force (BW)	2.30 ± 0.38	2.32 ± 0.36	2.35 ± 0.34	2.31 ± 0.33	2.33 ± 0.32
Maximum force (BW)	3.06 ± 0.20	3.06 ± 0.22	3.05 ± 0.22	3.00 ± 0.23	3.00 ± 0.23
Impulse (BW·s)	0.33 ± 0.02	0.33 ± 0.02	0.32 ± 0.02	0.32 ± 0.02	0.31 ± 0.02

Table 2. Mean (± SD) MAD scores (%) indicating variability at each distance.

	1500 m	3000 m	5000 m	7500 m	9500 m
Step length	0.67 ± 0.14	0.68 ± 0.13	0.65 ± 0.23	0.68 ± 0.15	0.71 ± 0.15
Step frequency	1.11 ± 0.33	1.18 ± 0.29	1.12 ± 0.40	0.97 ± 0.29	1.07 ± 0.33
Contact time	0.93 ± 0.34	0.78 ± 0.28	1.08 ± 0.74	1.04 ± 0.30	1.07 ± 0.66
Flight time	2.56 ± 0.66	2.26 ± 0.43	2.12 ± 0.70	2.15 ± 0.73	2.39 ± 0.75
Impact force	3.77 ± 0.74	3.55 ± 0.93	3.18 ± 0.71	3.15 ± 0.65	3.64 ± 0.89*
Maximum force	1.60 ± 0.29	1.32 ± 0.22*	1.48 ± 0.31	1.42 ± 0.32	1.50 ± 0.39
Impulse	1.27 ± 0.30	1.13 ± 0.25	1.08 ± 0.30	1.32 ± 0.35†	1.37 ± 0.58

A significant difference from the previous measurement is denoted as $p < 0.01$ (*) or $p < 0.05$ (†) based on repeated measures contrasts.

Table 3. Mean (± SD) symmetry angle scores (%) at each distance. Variables with a mean symmetry angle above 1.2% and mean Cohen's $d \geq 1.21$ are indicted with an asterisk (*).

	1500 m	3000 m	5000 m	7500 m	9500 m
Step length	0.42 ± 0.39	0.51 ± 0.46	0.53 ± 0.42	0.53 ± 0.45	0.54 ± 0.39
Step frequency	0.58 ± 0.52	0.56 ± 0.36	0.55 ± 0.49	0.56 ± 0.53	0.59 ± 0.46
Contact time	0.42 ± 0.35	0.33 ± 0.20	0.36 ± 0.22	0.45 ± 0.34	0.46 ± 0.34
Flight time	1.16 ± 0.92	1.14 ± 0.75	1.25 ± 1.03	1.40 ± 1.20*	1.29 ± 1.10*
Impact force	1.97 ± 1.47	2.87 ± 1.52*	2.74 ± 2.10*	2.65 ± 2.23*	2.77 ± 2.37*
Maximum force	1.00 ± 0.81	0.95 ± 0.70	1.01 ± 0.81	1.15 ± 0.87	1.12 ± 0.75
Impulse	0.86 ± 0.58	0.82 ± 0.59	0.92 ± 0.61	0.73 ± 0.46	0.81 ± 0.65

Table 4. Number (and percentage) of athletes at each distance who were considered asymmetrical for each variable (symmetry angle > 1.2% and Cohen's $d \geq 1.21$).

	1500 m	3000 m	5000 m	7500 m	9500 m
Step length	1 (7%)	2 (14%)	2 (14%)	1 (7%)	1 (7%)
Step frequency	2 (14%)	1 (7%)	1 (7%)	1 (7%)	1 (7%)
Contact time	0 (0%)	0 (0%)	0 (0%)	1 (7%)	1 (7%)
Flight time	3 (21%)	5 (36%)	5 (36%)	5 (36%)	5 (36%)
Impact force	4 (29%)	8 (57%)	9 (64%)	7 (50%)	9 (64%)
Maximum force	5 (36%)	5 (36%)	6 (43%)	5 (36%)	6 (43%)
Impulse	3 (21%)	2 (14%)	4 (29%)	5 (36%)	6 (43%)

Table 5. Mean (± SD) symmetry angle scores (%) across all five distances for each athlete. Athletes who had a mean symmetry angle above 1.2% (with Cohen's $d \geq 1.21$) and were asymmetrical at more than half the distances measured are indicted with an asterisk (*).

Athlete	Step length	Step frequency	Contact time	Flight time	Impact force	Maximum force	Impulse
1	0.55 ± 0.23	0.63 ± 0.15	0.11 ± 0.14	1.58 ± 0.45*	2.39 ± 1.05*	0.09 ± 0.06	0.34 ± 0.11
2	0.18 ± 0.08	0.58 ± 0.23	0.38 ± 0.12	0.89 ± 0.52	2.23 ± 0.54	0.19 ± 0.17	0.61 ± 0.37
3	0.14 ± 0.10	0.19 ± 0.27	0.26 ± 0.15	0.29 ± 0.34	2.65 ± 0.53*	0.72 ± 0.20	0.37 ± 0.34
4	0.38 ± 0.23	0.20 ± 0.09	0.33 ± 0.14	0.20 ± 0.15	0.75 ± 0.69	1.89 ± 0.36*	0.65 ± 0.43
5	0.16 ± 0.13	0.34 ± 0.21	0.30 ± 0.27	1.49 ± 0.44	0.97 ± 0.46	1.50 ± 0.27*	1.15 ± 0.24
6	1.31 ± 0.29*	0.31 ± 0.26	0.46 ± 0.24	0.64 ± 0.39	4.85 ± 2.02*	0.71 ± 0.17	1.37 ± 0.19*
7	0.30 ± 0.15	0.58 ± 0.28	0.39 ± 0.45	0.66 ± 0.44	1.25 ± 0.51	2.75 ± 0.58*	0.81 ± 0.32
8	0.68 ± 0.09	0.25 ± 0.28	0.45 ± 0.34	0.70 ± 0.37	6.58 ± 1.31*	1.20 ± 0.59*	1.05 ± 0.51
9	0.14 ± 0.10	0.96 ± 0.33	0.70 ± 0.26	1.27 ± 0.47	1.82 ± 0.92	0.72 ± 0.36	0.43 ± 0.27
10	0.24 ± 0.11	0.91 ± 0.24	0.24 ± 0.13	2.43 ± 0.59*	3.12 ± 0.96*	0.35 ± 0.13	0.29 ± 0.16
11	0.81 ± 0.19	0.51 ± 0.35	0.36 ± 0.15	1.33 ± 0.53*	3.00 ± 0.97*	1.47 ± 0.39*	0.81 ± 0.49
12	0.88 ± 0.15	0.30 ± 0.18	0.24 ± 0.19	0.50 ± 0.29	0.74 ± 0.38	1.24 ± 0.30	1.40 ± 0.23*
13	0.17 ± 0.13	1.73 ± 0.30*	0.62 ± 0.13	3.41 ± 0.64*	1.07 ± 0.86	0.48 ± 0.23	0.39 ± 0.21
14	1.10 ± 0.38	0.43 ± 0.25	0.81 ± 0.46	2.11 ± 0.89*	4.99 ± 1.03*	1.35 ± 0.35*	1.93 ± 0.54*

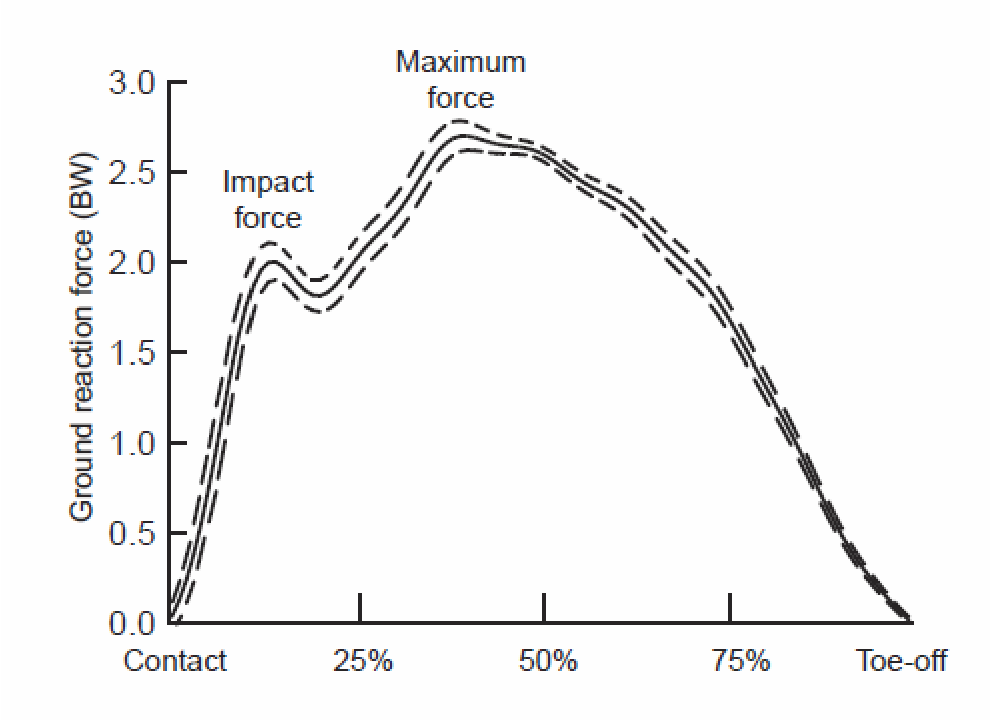

Figure 1. The mean (± SD) vertical GRF trace of the running stance phase for an individual runner at 1500 m.